Quantifying the Effect of Meteoroid Ablation Rate on Meteor Plasma Formation Using 3D Particle-in-Cell Simulation

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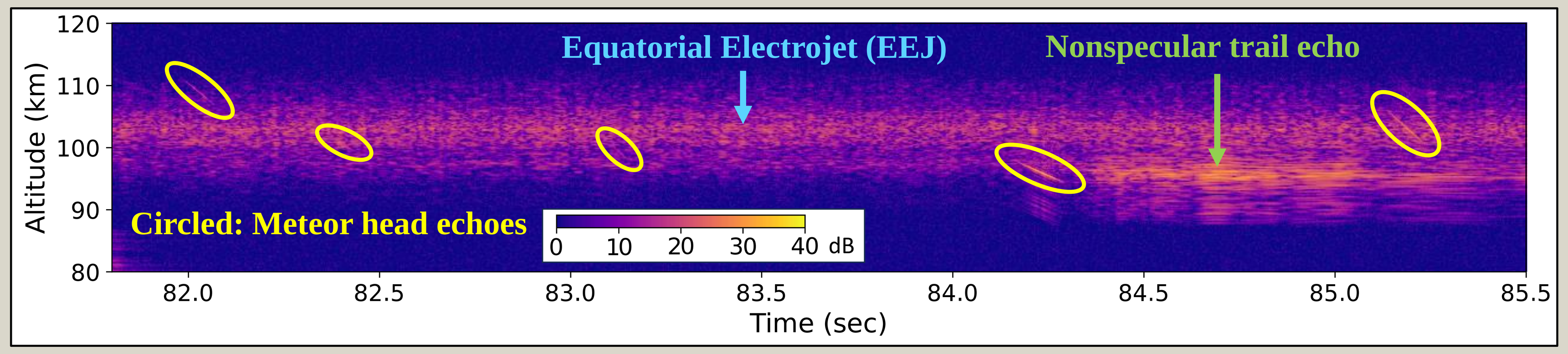
Background on Meteors via HPLA Radar

- **Thousands of meteors entering Earth's atmosphere per hour are observed by high-power large-aperture (HPLA) radar facilities**
- Meteoroids deposit metallic neutrals and ions into the atmosphere
- Meteor plasma becomes distinct component of ionosphere
- Meteoroid impacts pose mechanical and electrical hazards to spacecraft

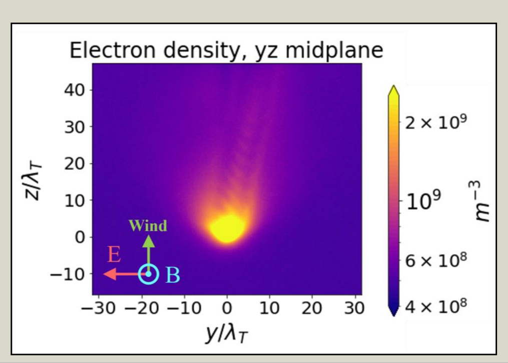


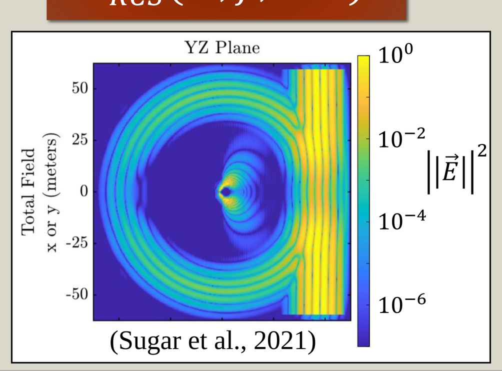
Meteors observed at Jicamarca Radio Observatory on October 10th, 2019 (Hedges et al., 2022)

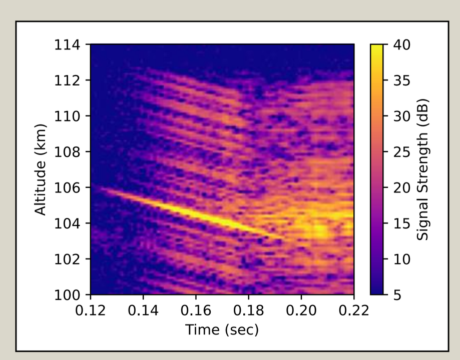
Why Simulate Meteor Plasma?

- Enormous and rich data sets of meteors observed via radar contain information about the meteoroids and the lower thermosphere
- Simulation tells us the shape of the electron density distribution surrounding a meteoroid, which is responsible for head echo observations
- **We seek to quantify, using particle-in-cell (PIC) plasma simulation, how head echo signal strength (σ_{RCS}), as seen in radar data, relates to meteoroid ablation rate ($\dot{m}$).** Can integrate $\dot{m}$ to get meteoroid mass (m)

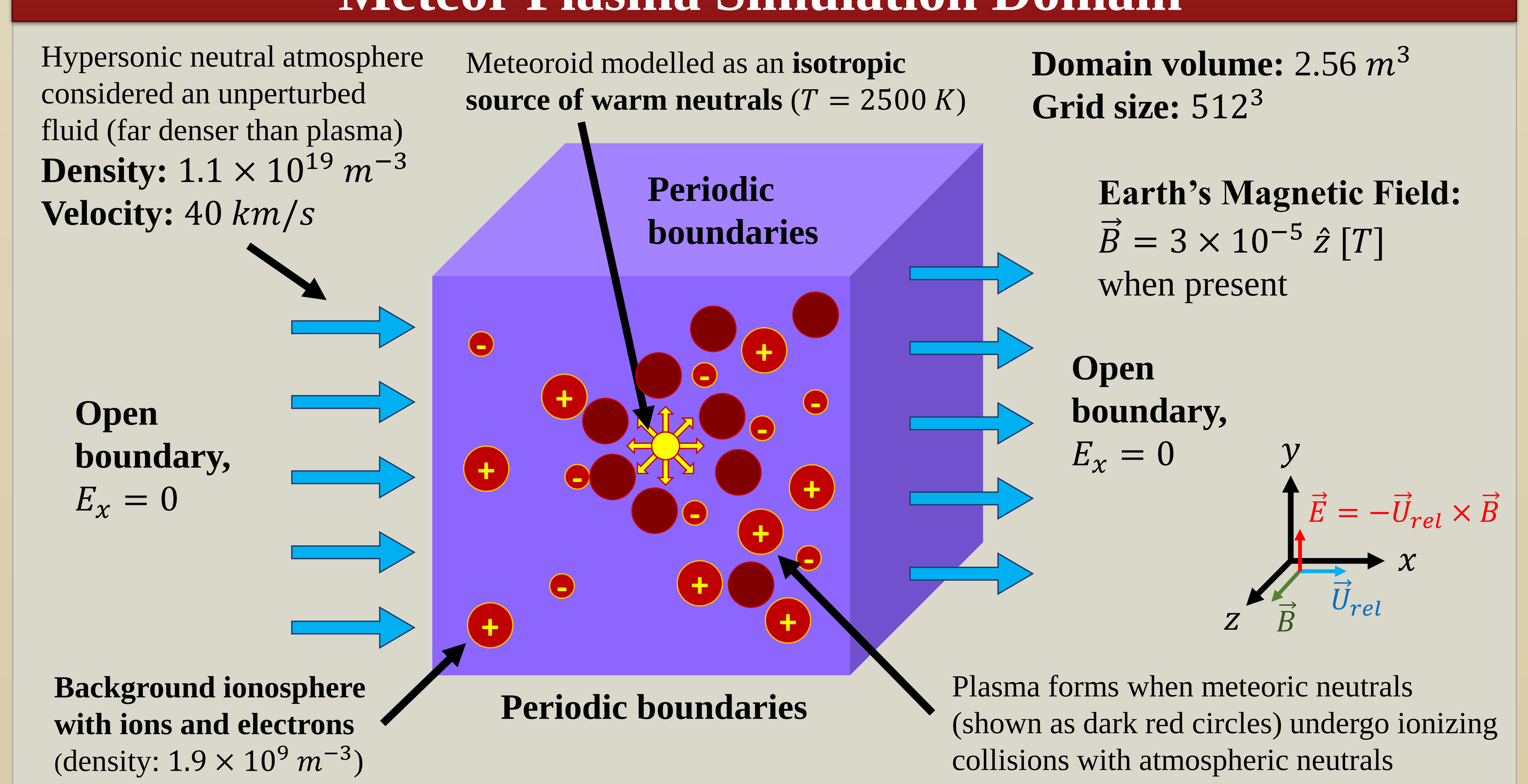
Simulate meteor plasma formation for various $\dot{m}$ **(this work)** → Simulate radar scattering from meteor, determine $\sigma_{RCS}(\dot{m}, f, etc.)$ → Use radar (with frequency f) to observe σ_{RCS}, determine $\dot{m}$







Meteor Plasma Simulation Domain



On a given timestep, the probability that a meteoric particle collides with an atmospheric particle determined via Monte Carlo collisions (MCC) method:

$$P_{col} = 1 - \exp(-U_{rel}\sigma_{MA}n_A\,\Delta t)$$

U_{rel} = Meteor velocity, σ_{MA} = coll. cross-section, n_A = atm. number density, Δt = timestep length

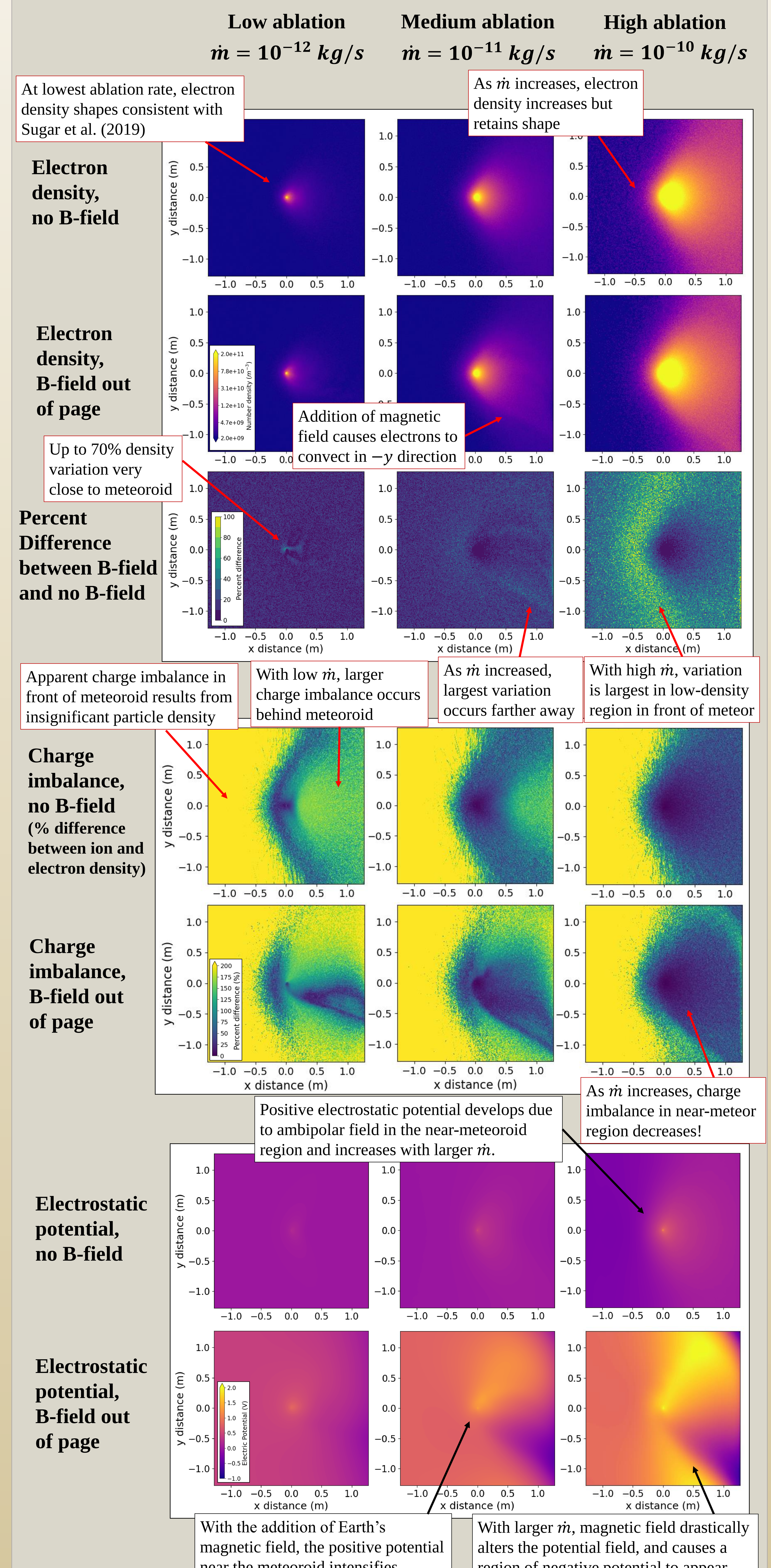
→ If a collision occurs, the probability that the meteoric particle ionizes is evaluated and assessed, as given by Vondrak et al. (2008):

$$P_{ion} = 0.933(U_{rel} - 8.86)^2 U_{rel}^{-1.94},$$

where U_{rel} is in km/s

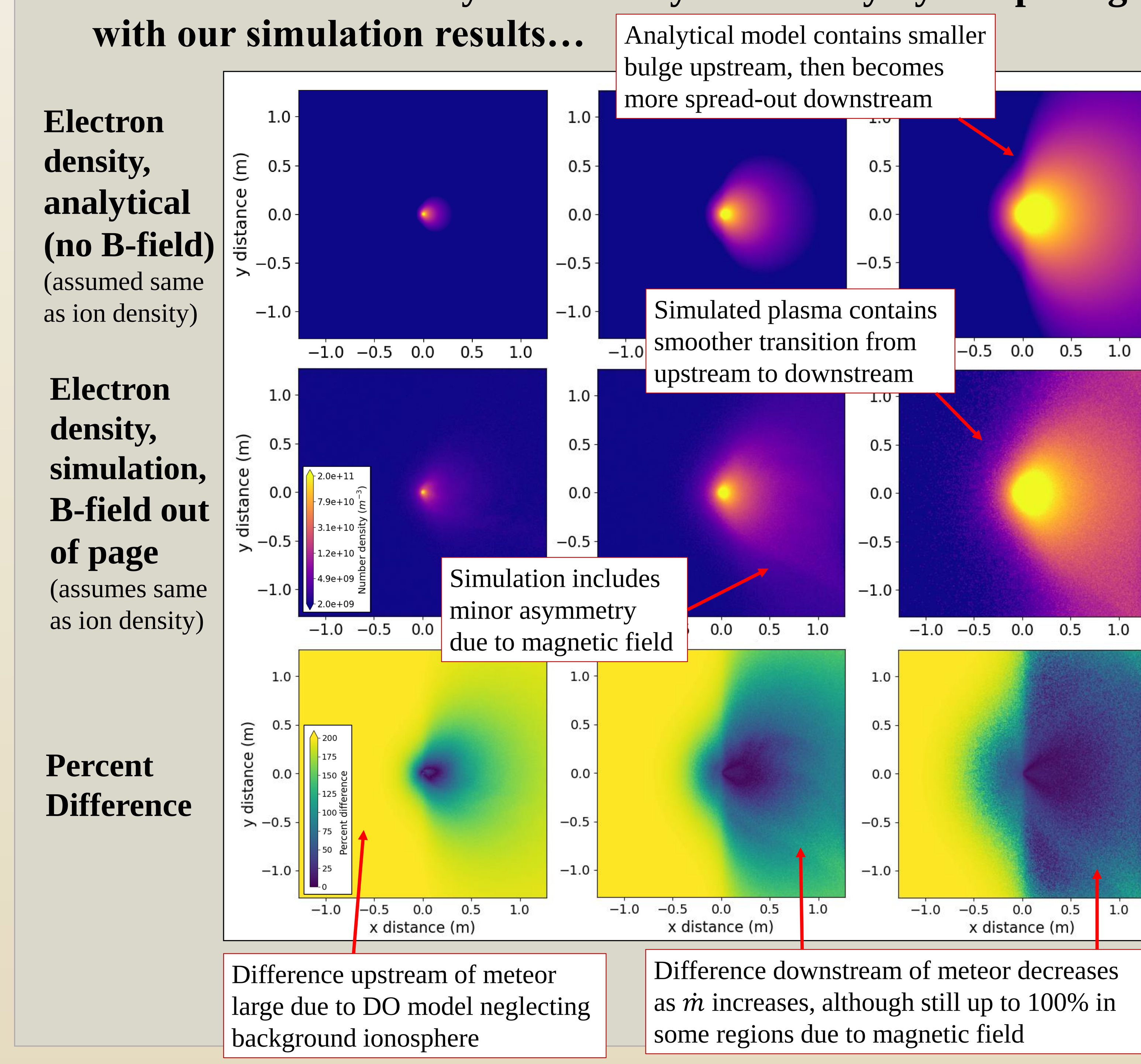
→ If ionization occurs, the neutral particle is deleted, and an ion and electron are generated.

Results



Comparison with Analytical Theory

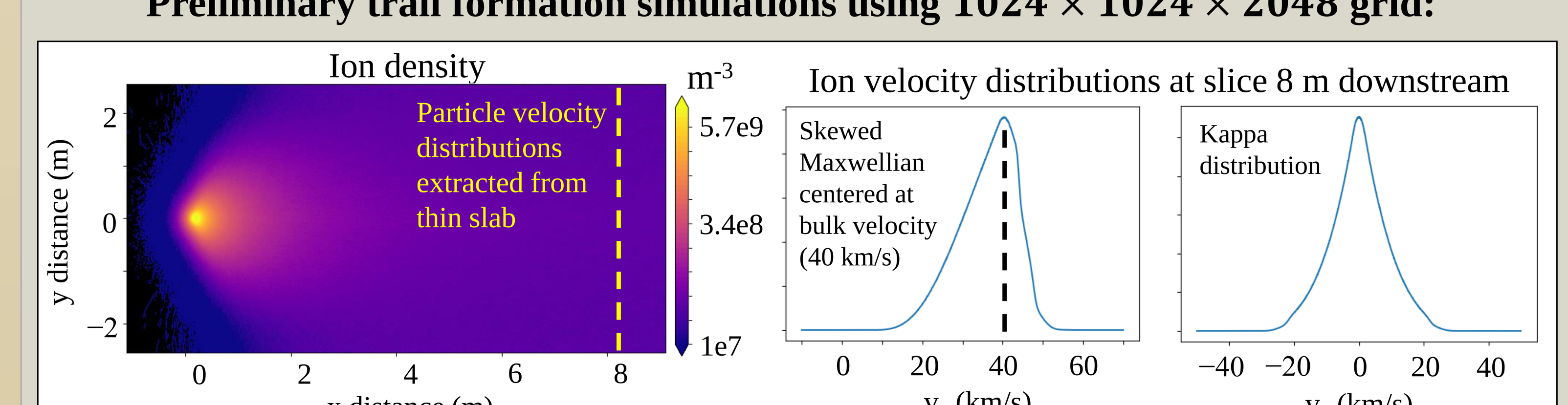
- Plasma density derived analytically by Dimant et al. (2017)
- Assumes particles only undergo one scattering collision
- Neglects electric and magnetic fields
- **We assess the accuracy of the analytical theory by comparing it with our simulation results…**



Conclusions and Future Work

- Effects of electric and magnetic fields in the head echo region of a meteor decrease as ablation rate ($\dot{m}$) increases
- Accuracy of analytical model increases as ablation rate increases, so long as collisions between meteoric particles remain negligible
- **This result lends credence to the analytical plasma density derived by Dimant et al. (2017) when used to interpret HPLA radar observations of meteors**
- Future work will extend domain size to include meteor trail formation, and utilize results to inform radar trail echoes

Preliminary trail formation simulations using $1024 \times 1024 \times 2048$ grid:



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